CHARACTERISTIC DISTRIBUTIONS OF ANGEL ECHOES IN THE LOWER ATMOSPHERE AND THEIR METEOROLOGICAL IMPLICATIONS*

BERNARD CAMPISTRON

Observatoire du Puy de Dôme, Centre de Recherches Atmosphériques, 65300 Lannemezan, France

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Abstract. Analysis of a vast series of angel echo observations made by a millimetric vertically-pointing radar reveals four major types of echo organization on height-time recordings. The relationship between the formation and development of these structures and the thermodynamic state of the atmosphere is clarified. The meteorological indicator role played by angel echoes is then discussed. In particular it is shown that in certain conditions, angel echoes can delineate the boundaries of small cumulus.

1. Introduction

Radar echoes from a clear atmosphere, usually called angel echoes, have been the subject of many studies (e.g., Friend, 1949; Atlas, 1959; Hardy *et al.*, 1966; Chernikov, 1966; Rowland, 1973; among others). The results and interpretations by various investigators have been summarized by Battan (1973), and will not be reviewed here.

There is now widespread acceptance that these echoes are caused primarily by insects, birds, or strong refractive index inhomogeneities of the air.

In the present state of our knowledge (Tatarsky, 1961; Atlas *et al.*, 1966; Ottersten, 1969; Hardy and Katz, 1969), and taking into account apparatus sensibility, refractive-index inhomogeneities seem a minor source of clear-air echoes for the 8.6-mm radar set of the Centre de Recherches Atmosphériques (CRA), the observations of which are the subject of this paper. The main source of angel echoes for this radar is certainly the reflections by material such as insects which are generally present in vast number in the lower atmosphere to heights of more than 3000 m during the hot months of the year (Berland, 1935; Glick, 1939).

Although at this short wavelength, the source of angel echoes is not an intrinsic atmospheric phenomenon, the analysis of numerous height-time recordings taken with the CRA millimetric vertically-pointing radar reveals several typical organizations of clear-air echoes in the lower atmosphere, the characteristics of which suggest close relations with meteorological factors.

There are numerous studies concerning angel echo patterns but in the majority of cases, these observations have been made with ultrasensitive centrimetric and decimetric radars which have indeed detected refractive index inhomogeneities of the air (Hicks and Angell, 1968; Ottersten, 1969; Atlas *et al.*, 1970; Konrad, 1970; Rowland, 1973).

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In the millimetric band, such studies are relatively scarce and always fragmentary. The purpose of this article is, from an analysis of a vast series of records taken with an 8.6-mm vertically pointing radar, to exhibit the principal angel echo patterns, to propose a classification of them, and to try to show correlations with thermodynamic factors. In the last part of this paper, the use of these patterns as a meteorological indicator is then discussed.

2. Experimental Conditions

The set was a pulse radar constructed in 1966 to study the fine structure of clouds (Sauvageot, 1968). Its main characteristics are as follows:

wavelength (cm)	0.86
transmitted power (kW)	100
pulse duration (μs)	0.5
pulse repetition frequency (Hz)	1200
beam width at 3 dB (deg)	$E=0.4$; $H=0.7$
minimum detectable power (dBm)	-98

The radar observations used in this paper were made with a vertical beam. Recordings were obtained as follows: the signals received from the atmosphere were sampled by a mobile analysis gate, integrated, and presented in the form of a height-time diagram, by means of a facsimile recorder. The successive data constituted an observation surface. An automatic sequential signal attenuator permitted quantified determination of the echo power. A switchable distance correction circuit (DCC), acting through the first three kilometers of the atmosphere, compensated for the signal weakening caused by distance.

The bulk of the observations employed were gathered during a survey of the lower atmosphere which took place in June 1971 at Chateauroux (altitude 160 m, 46° 50′ N, 1° 42′ E). The available observations covered nine days, representing over 84 hr of recordings in variable meteorological conditions. These data were exploited with the aerological measurements taken regularly near the experimental site, including hourly wind soundings by radar, three temperature and humidity radiosoundings daily between 0800 and 1800, *in situ* meteorological observations and measurements by the aircraft of the Centre Aérien d'Etudes Météorologiques. The many recordings taken at the Centre de Recherches Atmosphériques (altitude 600 m, 43° 7′ 41″ N, 0° 22′ 12″ E) supplemented the data gathered at Chateauroux.

3. Source of the Angel Echoes

At 8.6 mm as for other wavelengths, there are two types of radar echoes from a clear atmosphere: (a) dot or point angel echoes similar to echoes which would be given by small particles crossing the radar beam; and (b) incoherent angel echoes having the fluctuating characteristics of precipitation retrodiffusion.

The works of Hardy *et al.* (1966) on the dependence between angel backscattering cross-section and wavelength, and the depolarization investigations of dot angels carried out by Chernikov (1966) and Battan and Lofgren (1969), provide convincing evidence that the overwhelming majority of dot angel echo targets are insects and other atmospheric particles. The explanation suggested by Friend (1949) and Atlas (1965) that dot angels could originate from specular reflection from regions of the atmosphere having high refractive-index gradients is no longer widely accepted.

The 8.6-mm wavelength is particularly useful for the detection of small particles. At this wavelength, the radar cross-section of a midge is 2×10^{-2} cm^2, and that of a fly is 1.5×10^{-1} cm^2 (Campistron, 1973). Such targets can well explain dot angels detected by the CRA radar set, the cross-sections of which range from less than 10^{-3} cm^2 to 5×10^{-1} cm^2.

Radar reflectivities of incoherent angels obtained with the CRA radar set range from 10^{-13} cm^{-1} to 10^{-11} cm^{-1}. Taking into account scattering theory for the refraction of turbulent clear air (Tatarsky, 1961; Ottersten, 1969), and taking into account data obtained from such retrodiffusions by ultrasensitive centimetric and decimetric radars (Hardy *et al.*, 1966; Kropfli *et al.*, 1968; Hardy and Katz, 1969; Starr and Browning, 1972), it seems very improbable that these high 8.6-mm radar reflectivities result from scattering caused by refractive index inhomogeneities. At this short wavelength, the source for incoherent angels is certainly insects or other particles dispersed in such a fashion that their spacings are generally less than the resolution distance of the radar.

It is interesting to note that Hardy and Ottersten (1969) explain by insect scatterings, reflectivities as high as 3×10^{-12} cm^{-1} detected by a 3.2-cm radar; in the same way Hardy and Katz (1969) draw the same conclusion to account for reflectivity values of about 6×10^{-12} cm^{-1} reported by Atlas (1960) using a 1.25-cm radar set.

4. Main Types of Echo Organization

The angel echoes observed from the ground by the millimetric radar fill a layer generally not exceeding 3000 m in thickness on the height-time recording. The echo frequency presents a maximum between April and October, during the hot months of the year when the layer is thickest, and a minimum in winter. The effect of temperature on the phenomenon is shown in Figure 1.

A diurnal cycle is superimposed on this annual cycle. In general, the height of the top of the layer rises steadily in the morning, goes through a maximum in the early afternoon, and declines to a minimum at night. During the month of June 1971, the 'morning rise' occurred at an average speed of 7 m min^{-1}. It should be noted that during this month, the height of the top of the echo layer was always greater than that of the dry convection layer (Figure 2), and that the echoes were originating at heights where temperatures were positive. This last observation is closely connected to the fact that angel echoes are practically nonexistent when the surface temperature is negative. These diurnal and annual cycles are reported by numerous investigators such as Atlas (1959).

Despite the wide variety of angel echo recordings, it appears that the data can be classified into four main categories corresponding to four basic types of echo organization in the lower atmosphere:

TYPE I – HOMOGENOUS LAYER

The echoes decrease in number and power with altitude. The vertical signal distribution as a function of time varies only slightly (Figure 3a).

TYPE II – THIN STRATIFORM LAYERS

At certain altitudes, the number and power of the echoes exhibit maxima, forming thin horizontal layers ranging from one hundred to a few hundred meters in thickness. Figure 3b illustrates three sheets of this type: at 1230 LST, the lowest layer is located

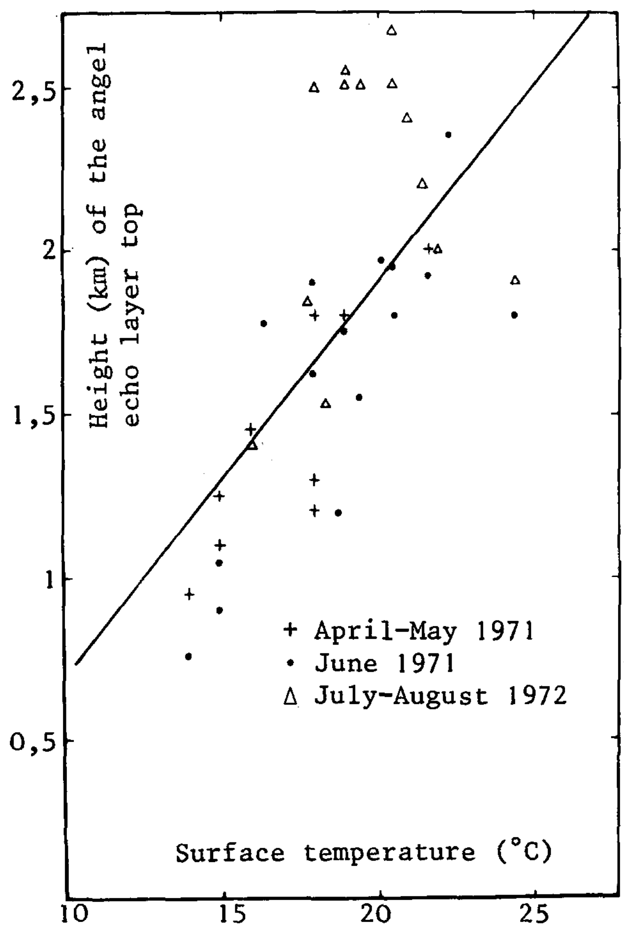


Fig. 1.

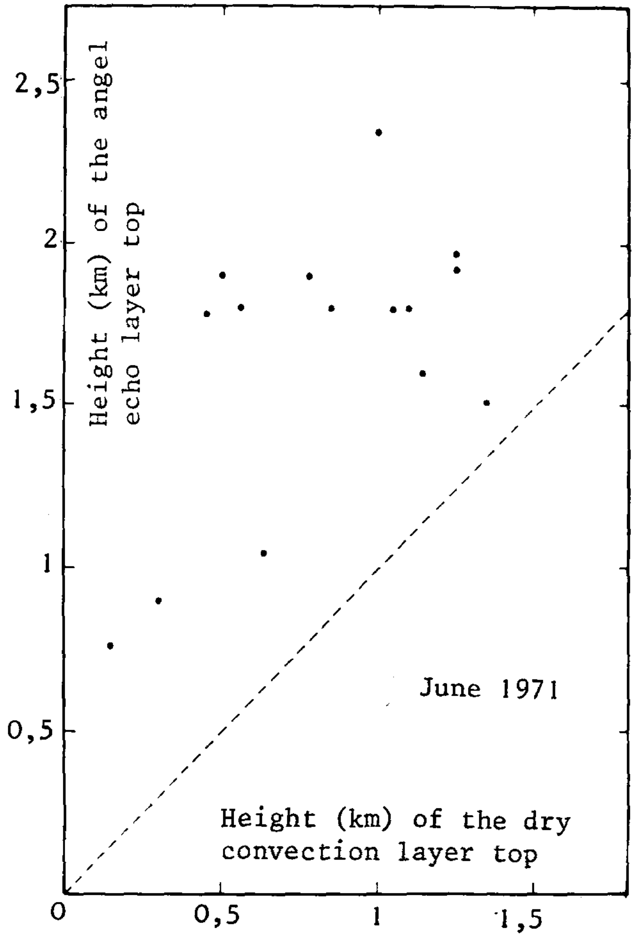


Fig. 2.

Figs. 1 and 2. Height of the top of the angel echo layer as a function of surface temperature (Figure 1) and of the height of the top of the dry convection layer (Figure 2).

between 850 and 1000 m altitude, the central, most clearly defined layer lies between 1300 and 1450 m, and the highest lies between 1600 and 1850 m. These stratifications are capable of persisting for several hours, their mean altitude varying slowly in the course of a day.

TYPE III – CUMULIFORM STRUCTURES

The echoes are sometimes clustered in cells resembling small cumulus clouds in shape and size. The base of these cumuliform structures is located at ground level in most cases. Figure 3c is an example of this type of organization. Assuming that the scattering elements producing the echoes drift with the wind at their level, a horizontal dimension of 2.4 km is found at a height of 800 m; the top of the cell passes above the radar at 1620 LST. Hence, unlike type I the vertical echo distribution is no longer constant with time, but exhibits a modulation. While the cells are joined in cases shown in Figure 3c, they are frequently observed separately as in Figure 11 or also in Figure 3b below 800 m.

TYPE IV – CLEAR ZONES

Echo-free zones are sometimes encountered within the layer. These clear zones, which are fairly limited in size, exhibit transit times generally not exceeding 10 min (Figure 3d).

THE GENERAL CASE

In general, the echo distribution consists of an overlapping of several types of organization, which vary with time as shown by the example in Figure 3e.

An analysis of echoes shows that these clear air patterns may consist of dot angels and incoherent angels.

5. Relationship Between Angel Echo Organizations and Meteorological Conditions in the Lower Atmosphere

Most angel echo recordings can be described by referring to the four types of distribution postulated above. As may be seen, these various types reflect thermodynamic conditions in the lower atmosphere.

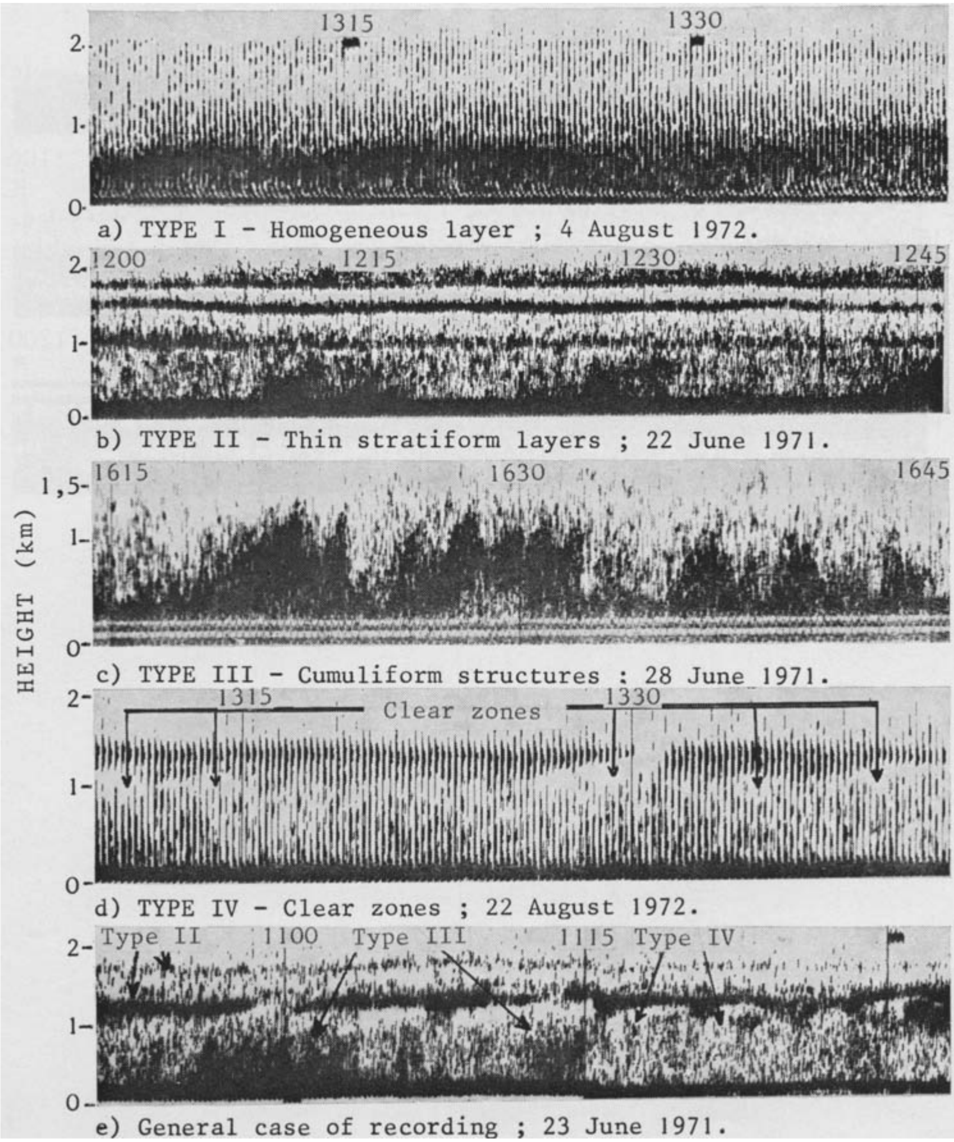
A. STRATIFORM ANGEL STRUCTURES

Stratiform structures are observed whatever wavelength is used. They have been known and studied for a long time (Friend, 1949).

Analysis of the observations shows that, of all meteorological parameters, the vertical temperature profile is the main criterion which determines the presence or absence of angel echo stratiform structures (type II). These stratiform angel concentrations are all located above the surface convective layer, and are within or at the boundaries of zones in which the vertical temperature gradient is positive or null. When penetrative convection reaches a stratified angel structure, it has been observed that the latter disappears, whereas the associated inversion may persist for a longer period.

The recording of 22 June 1971 (Figure 4) shows the formation and disappearance of radar stratifications during the morning. This day is characterized by multiple stratifications. Thin layers appear successively at increasing altitudes, and are plotted in Figure 4 by order of appearance (a, b, c, d). The first (a) is formed at about 0845 between 400 and 500 m; according to the 0810 sounding, it is located in the lower part of a temperature inversion, which extends from 440 to 540 m. This echo layer begins to disintegrate at 1025 and disappears at 1135. Its disappearance seems to be associated with penetrative convection, since, according to flight observations at 1000, there were cumulus at 450 m with tops at 700 m. This inversion failed to appear on the 1050 sounding, in which the convection layer was topped by an isothermal layer between 570 and 670 m altitude, surmounted by an inversion.

In addition to the inversion layer mentioned above, three stable zones can be distinguished on the 0810 sounding: an inversion between 840 and 1040 m, and two isothermal layers, one of which lies between 1440 and 1540 m and the second between 1780 and 1950 m. At the time of the sounding, very few echoes occur at these altitudes; at 0915, however, a radar stratification (b) appears between 800 and 1000 m, another (c) at 1005 between 1400 and 1600 m, and a third (d) at 1100 between 1650 and 1800 m.



Figs. 3. Classification of angel echo structures as observed using a vertically pointing radar and height-time facsimile recordings. For recordings b and e, the DCC is used. For recordings a and d, 6 signal intensity levels are used, ranging between 0 and 30 dB by 6 dB steps.

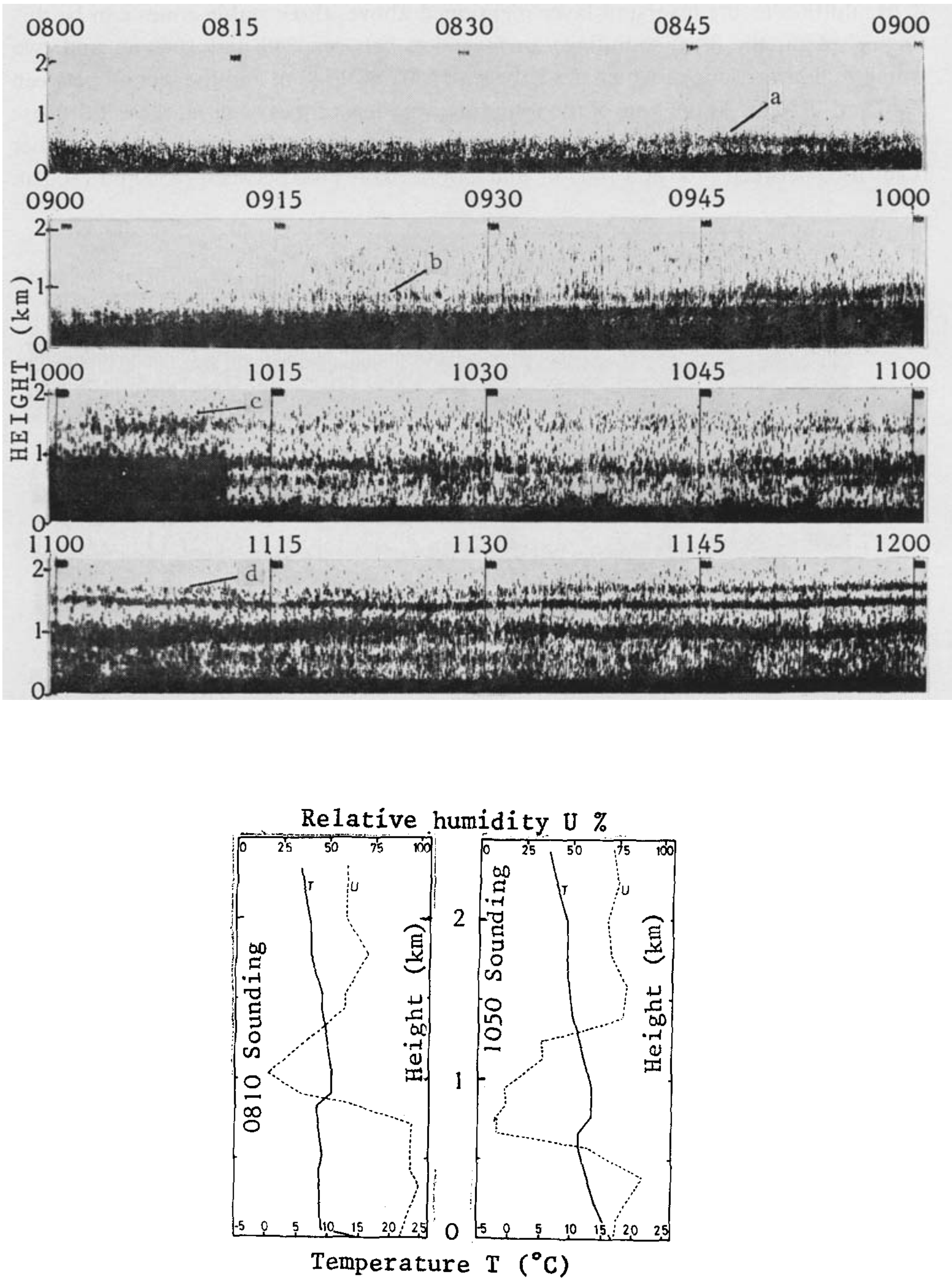


Fig. 4. Morning development of thin stratiform layers on 22 June 1971. Recording without sequential attenuation and using the DCC from 1010. Below, temperature and relative humidity sounding taken during this period.

Hence, while the maximum echo height and frequency increase during the morning, their confinement to stable layers still present on the 1050 sounding becomes steadily more pronounced.

The stability conditions are such that recordings with and without type II structures must correspond to air masses with different thermodynamic profiles. An examination of the meteorological conditions confirms this hypothesis.

In order to see this, some wind distributions (Figures 5 to 8) based on aerological data taken at 100-m intervals in the angel echo layer are shown for echo stratification

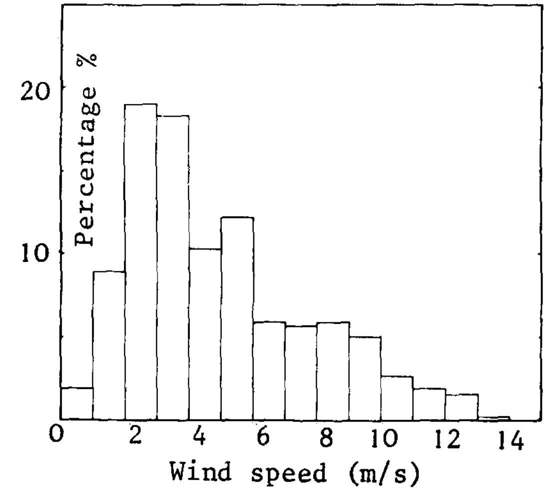


Fig. 5.

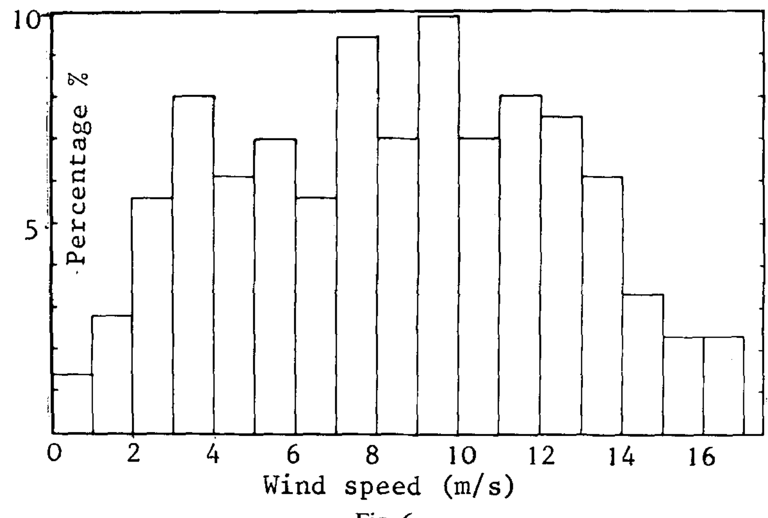


Fig. 6.

Figs. 5 and 6. Wind speed distribution in the angel echo layer for the June 1971 recordings with echo stratifications (Figure 5) and for the other recordings of this month (Figure 6).

and for all other cases. Similarly, the mean temperature gradients are plotted at 200-m intervals in Figures 9 and 10 for the angel echo zones, and for all other cases, respectively.

Angel echo stratifications are associated with warmer, quieter air masses (Figures 5 and 6). Although the prevailing wind is westerly, other directions are also associated with Type II structures (Figure 7), which is not true for other cases (Figure 8).

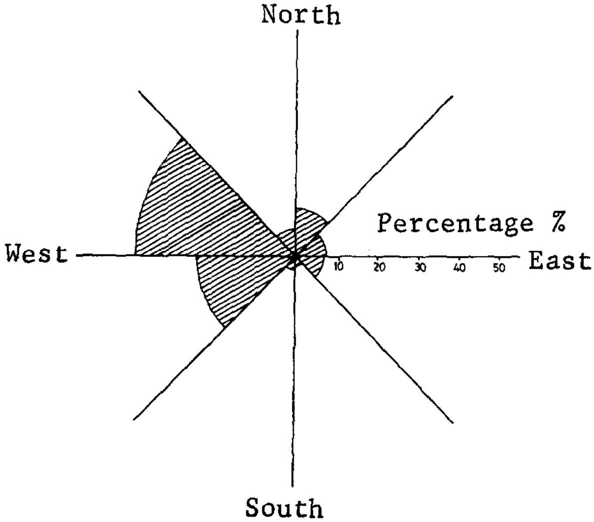


Fig. 7.

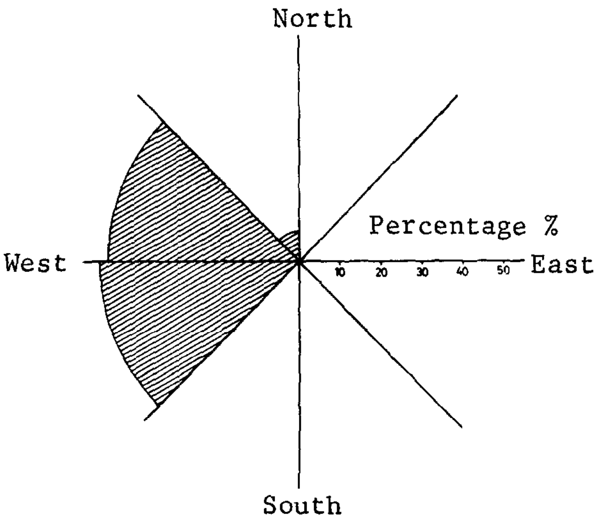


Fig. 8.

Figs. 7 and 8. Wind direction distribution in the angel echo layer for the June 1971 recordings with echo stratifications (Figure 7) and for the other recordings of this month (Figure 8).

The greater instability encountered on days without angel stratification (Figures 9 and 10) reflects a more highly developed cloud system of the cumulus congestus type. On the other hand, on days exhibiting type II structures, the clouds are cumulus mediocris, with tops rarely rising above 1500 m, and with a maximum thickness of 500 m.

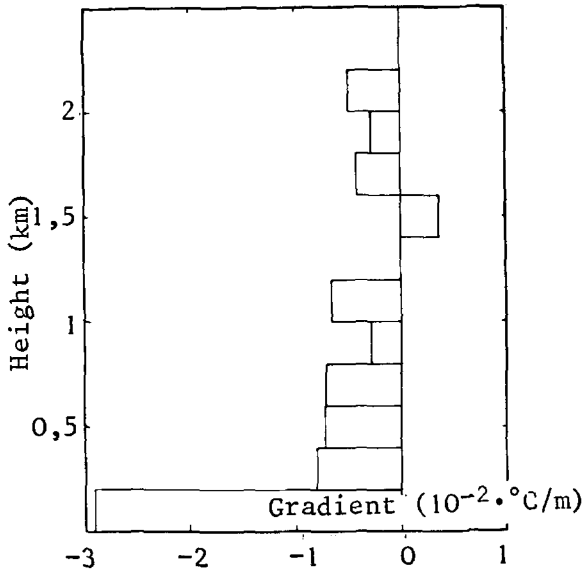


Fig. 9.

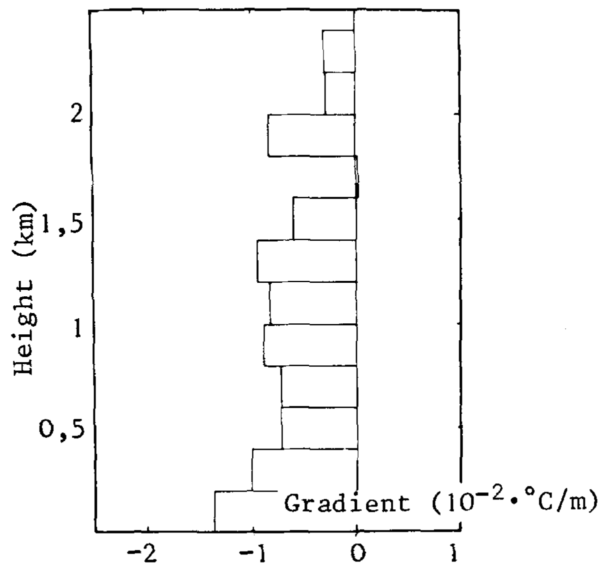


Fig. 10.

Figs. 9 and 10. Mean temperature gradient as a function of height for the June 1971 recordings with echo stratifications (Figure 9) and for the other recordings of this month (Figure 10).

The thermal and dynamic stability of anticyclones is favourable for the formation and persistence, at certain altitudes, of thin quasi-laminar layers. This layering of the atmosphere is revealed by echo stratifications, as shown by the example of 22 June 1971.

Generally these thin layers are regions of large refractive-index gradients which yield incoherent angels when observed by sensitive centimetric or decimetric radars (Lane, 1968) (Hicks and Angell, 1968).

B. CUMULIFORM ANGEL STRUCTURES

When cumulus clouds are only slightly developed or nonexistent (particularly on stratification days), type III angel structures are few in number (Figure 11). The contrary occurs when instability is high in the lower atmsophere and, in certain cases, it is not possible to distinguish one cumuliform angel cell from another (Figure 3c). In this example, the cumulus clouds (undetectable by radar because they consist of very small droplets) have their bases at 1200 m, in other words, at the top of the angel echo cells. It should be noted that the top of these cells is always lower than the lowest existing angel stratification, as shown in Figure 11. These remarks suggest that this type of echo organization is associated with instability, and hence with convection.

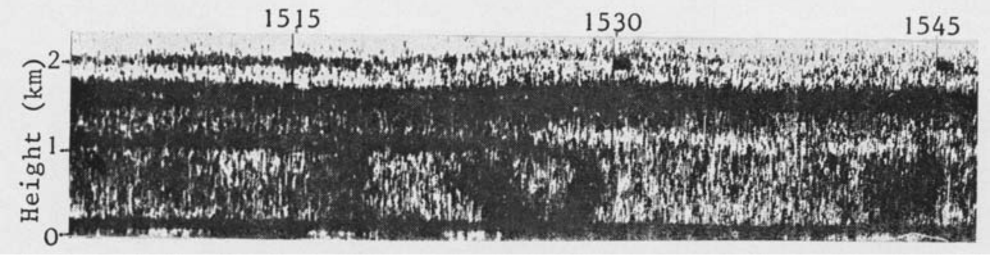


Fig. 11. Recording using the DCC and without sequential attenuation; 22 June 1971.

This is partially confirmed by Figure 12: during the month of June 1971 the cumuliform angel structures are formed in the dry convective layer; their tops occurred near the upper level of dry convection.

Consequently, the echo concentration in thermal ascents, which are convergent zones, appears to be the cause of type III organizations, which thus depict the organization of dry convection near the ground.

These cumuliform angel concentrations, already observed by Chmela and Armstrong (1955) with a 1.25-cm vertical beam radar, and detected by radars of greater wavelengths (Hardy and Ottersten, 1969; Konrad, 1970) seem to have a common origin the angel source is not always the same.

C. CLEAR ZONES

Visual observation of the sky shows that clear zones coincide with the transit of cumulus above the radar. Moreover, local observations made by the aircraft of the Centre Aérien d'Etudes Météorologiques during the recording period of 23 June 1971

(Figure 3e) indicate that the height and thickness of the cumulus correspond exactly to those of the clear zones. Thus these type IV structures identify the location of cumulus humilis or mediocris, which are undetectable by radar. In this way, these clouds, which do not contain sources of angel echoes, leave their signature. 'Detected' indirectly, their progress can subsequently be followed (Campistron, 1972; Campistron and Sauvageot, 1974).

The indirect detection of cumulus, to our knowledge, has not yet been reported by other investigators. Let us note, however, that Richter *et al.* (1973) with a high resolution decimetric FM-CW radar observed the upper boundary of small cumulus (undetectable by this radar) due to backscattering from refractive index inhomogeneities of the clear air at this level.

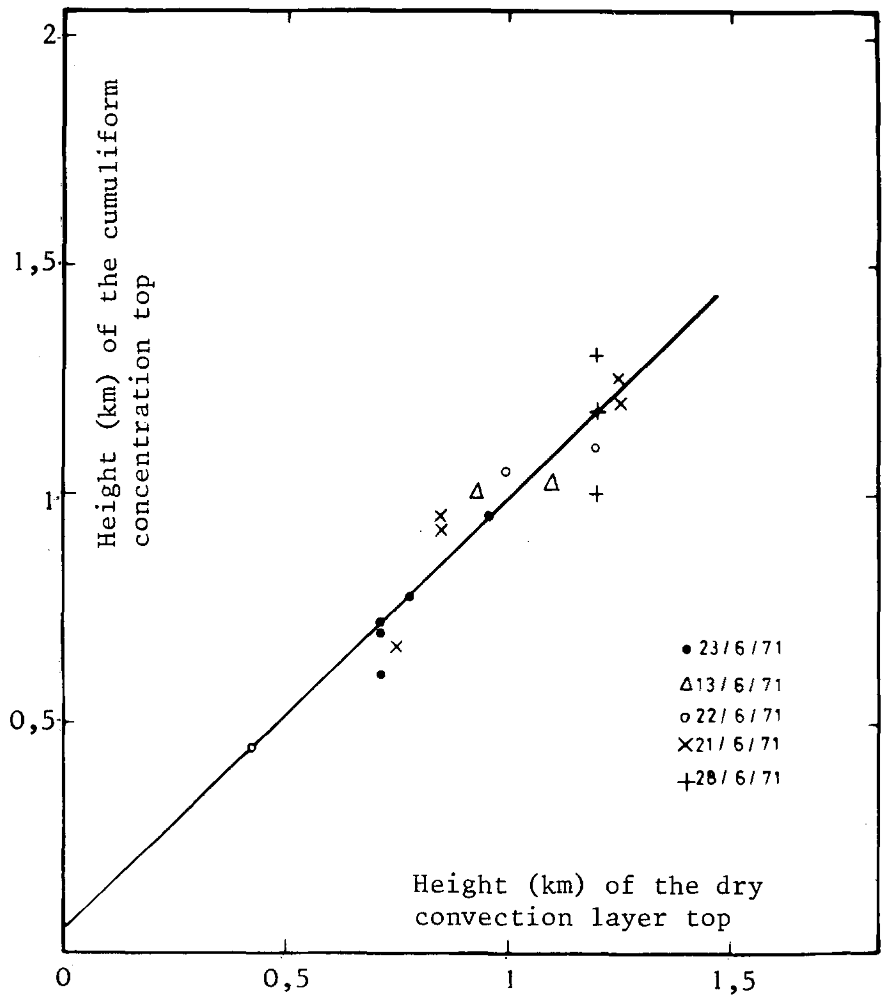


Fig. 12. Height of the top of the cumuliform echo structure as a function of the height of the top of the dry convection layer for June 1971 recordings.

It should be noted that convective activity linked to these clear zones (i.e., small cumulus) is frequently responsible for the disruption and disappearance of type II structures (Figures 3d and 3e).

Consequently, structures of types III and IV have a common origin in instability, and are, moreover, often found together on recordings (Figure 3e). However, while type III visualizes dry convection, type IV visualizes wet convection.

D. HOMOGENEOUS LAYER

The formation of a homogeneous layer is associated with the absence of the thermodynamic structures which cause the three other types of organization. It therefore results from the absence of highly stable air layers or intense, localized convective movements in the lower atmosphere. It can be ascribed to homogeneous, weak convection.

6. Remarks and Conclusions on the Use of Angel Echoes in Studies of the Lower Atmosphere

The sampling of angel echo observations made by a millimetric vertically beamed radar system, accompanied by frequent meteorological measurements, has revealed the existence of four main types of echo organization. The characteristics of these four structures and their relationships with thermodynamic conditions are summarized below:

Type I: Echo density and power decreasing with altitude and varying slightly with time.

Type II: Stratiform echo structure in a thin layer due to high local stability.

Type III: Concentration of echoes in cumuliform cells associated with dry phase convection.

Type IV: Clear zone identifying the location of cumulus humilis and mediocris in the angel echo layer.

To each thermodynamic state of the atmosphere corresponds a category of cloud, the characteristic pattern of which reflects its process of formation. A study of radar recordings of cloud systems thus permits the determination of local meteorological situations by recognition of cloud shapes (Boucher, 1959). Similarly, based on the foregoing results, the identification of various types of angel echo organization can provide valid information on thermodynamic structures in the lower atmosphere.

However, the utilization of clear-air echoes as tracer is restricted to the first three kilometers of the atmosphere, and is available only when angels are in sufficient concentration, that is to say during the hot months of the year from June to September.

Echo stratifications associated with high stability zones are especially numerous in anticyclone air masses. The monitoring of these thin layers (appearance, number, movement, duration) can provide valuable information on changes in vertical thermal profiles. The fact that these structures are located above the convective zone can also be taken into account.

Cumuliform structures associated with convective instability can indicate dry convection intensity and height, by their number and development. They thus depict thermal convergence zones which generate turbulence.

The presence of a uniformly distributed echo layer is associated with an air mass not exhibiting any zone of high local stability and is weak and homogeneous or non-existent.

It is also possible to follow the progress and behaviour of small cumulus undetectable by radar, with the clear zones which they create in the angel echo layer.

Apart from the problem of the nature of echoes in clear sky, the possibility of using angel echoes in investigations of the lower atmosphere thus expands the scope of activity of millimetric radar, for which they constitute highly effective natural tracers.

References

Atlas, D.: 1959, 'Radar Studies of Meteorological Angel Echoes', *J. Atmos. Terrest. Phys.* **15**, 262--287.

Atlas, D.: 1960 'Radar Detection of the Sea Breeze', *J. Meteorol.* **17**, 244–258.

Atlas, D.; 1965, 'Angels in Focus', *Radio Sci.* **6**, 871–875.

Atlas, D., Hardy, K. R., and Naito, K.: 1966, 'Optimizing the Radar Detection of Clear Air Turbulence', *J. Appl. Meteorol.* **50**, 450–460.

Atlas, D., Metcalf, J. I., Richter, J. H., and Gossard, E. E.: 1970, 'The Birth of 'CAT' and Microscale Turbulence', *J. Atmos. Sci.* **27**, 903–913.

Battan, L. J.: 1973, 'Radar Observation of the Atmosphere', University of Chicago, 324 pp.

Battan, L. J. and Lofgren, G. R.: 1969, 'Polarization and Vertical Velocities of Dot Angel Echoes', *J. Appl. Meteorol.* **8**, 948–951.

Berland, L. J.: 1935, 'Premiers résultats de mes recherches en avion sur la faune et la flore atmosphériques', *Ann. Soc. Ent. France* **104**, 73–97.

Boucher, R. J.: 1959, 'Synoptic-physical Implications of 1.25 cm Vertical Beam Radar Echoes', *J. Meteorol.* **16**, 312–326.

Campistron, B.: 1972, 'Intérêt des échos fantomes détectés par le radar 8.6 mm comme traceur pour l'étude des basses couches de l'atmosphère', *Colloque sur la Physique de la Basse Atmosphère, Lille*, avril 1972.

Campistron, B.: 1973, 'Relation entre les échos fantomes observés avec un radar 8.6 mm et l'état thermodynamique de la basse atmosphère', *Thèse de 3ème Cycle*, Université de Toulouse, no. 1415.

Campistron, B. and Sauvageot, H.: 1974, 'Sur l'évolution matinale de la distribution dans l'espace des échos radar en air clair', *Compt. Rend. Acad. Sci. Paris*, octobre 1974, série B, 479–482.

Chernikov, A. A.: 1966, 'Some New Soviet Investigations of Angel Echoes', *Proc. 12th Weather Radar Conf.* Boston: Am. Meteorol. Soc., 291–292.

Chmela, A. C. and Armstrong, G. M.: 1955, *Proceedings Fifth Weather Radar Conference*, Asbury Park, pp. 63–66.

Friend, A. W.: 1949, 'Theory and Practice of Tropospheric Sounding by Radar', *Proceedings of the IRE*, 116–138.

Glick, P. A.: 1939, 'The Distribution of Insects, Spiders and Mites in the Air', *Tech. Bull. U.S. Dep. Agric.*, No. 673, 150 pp.

Hardy, K. R., Atlas, D. and Glover, K. M.: 1966, 'Multiwavelength Backscatter from the Clear Atmosphere', *J. Geophys. Res.* **71**, 1537–1552.

Hardy, K. R. and Katz, I.: 1969, 'Probing the Clear Atmosphere with High Power, High Resolution Radars', *Proceedings of the I.E.E.E.* **57**, 468–480.

Hardy, K. R. and Ottersten, H.: 1969, 'Radar Investigation of Convective Patterns in the Clear Atmosphere', *J. Atmos. Sci.* **26**, 666–672.

Hicks, J. J. and Angell, J. K.: 1968, 'Radar Observations of Breaking Gravitational Waves in the Visually Clear Atmosphere', *J. Appl. Meteorol.* **7**, 114–121.

Konrad, T. G.: 1970, 'The Dynamics of the Convective Process in Clear Air as Seen by Radar', *J. Atmos. Sci.* **2**, 1138–1147.

Kropfli, R. A., Katz, I., Konrad, T. G., and Dolson, E. B.: 1968, 'Simultaneous Radar Reflectivity Measurements and Refractive Index Spectra in the Clear Atmosphere', *Radio Sci.* **3**, 991–994.

Lane, J. A.: 1968, 'Small-Scale Variations of Radio Refractive Index in the Troposphere', *Proc. I.E.E.* **115**, 1227–1239.

Ottersten, H.: 1969, 'Atmospheric Structure and Radar Backscattering in Clear Air', *Radio Sci.* **4**, 1179–1193.

Richter, J. H., Jensen, D. R., Pappert, R. A., and Noonkester, V. R.: 1973, 'New Developments in FM-CW Radar Sounding', *Boundary-Layer Meteorol.* **4**, 179–199.

Rowland, J. R.: 1973, 'Intensive Probing of a Clear Air Convective Field by Radar and Instrumented Drone Aircraft,' *J. Appl. Meteorol.* **12**, 149–155.

Sauvageot, H.: 1968, 'Participation à une étude détaillée de l'environnement atmosphérique local. Prévision à court terme', *Rapport D.R.M.E. de synthèse 64–349.*

Starr, J. R. and Browning, K. A.: 1972, 'Doppler Radar Measurements of Clear Air Turbulence', *15th Radar Meteorology Conference*, pp. 248–251.

Tatarsky, V. I.: 1961, *Wave Propagation on a Turbulent Medium*, New-York, McGraw-Hill, 285 pp.